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STORAGE PHOSPHOR READOUT SYSTEM USING RESONANT MICROCAVITY CONVERTER

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STORAGE PHOSPHOR READOUT SYSTEM USING RESONANT MICROCAVITY CONVERTER

FIELD OF THE INVENTION

This invention relates in general to a readout and detection system for storage phosphor screens used in radiographic imaging systems. More particularly, it relates to the inclusion in such a system of a device that converts electromagnetic radiation emitted from the screen in a wide angular distribution at one wavelength band into a narrower cone of emission at a longer wavelength band.

BACKGROUND OF THE INVENTION

Storage phosphor based radiographic imaging systems (computer radiography) are currently in widespread use. These systems use screens containing phosphor material that store a portion of the incident ionizing radiation as latent storage sites. These sites are subsequently stimulated to release electromagnetic radiation (the stimulated emission), typically in the 350 to 450 nanometer range, in proportion to the amount of ionizing radiation that was absorbed by the phosphor material. The typical readout method used in these systems is the so-called flying-spot scanning method. A focused laser beam, typically in the 600 to 700 nanometer range, is raster scanned over the surface of the screen to stimulate the storage sites. Synchronously, the stimulated emission is collected, detected, and digitized. The pixel size of the image is determined by the raster rate and digitization rate. After readout, the screens are flooded with erasing light to remove any remaining storage sites so the screen can be reused.

An alternative configuration described in U.S. Patent 6,373,074, issued April 16, 2002, inventors Mueller et al., and U.S. Patent Application Publication 2002/0008212A1, published January 24, 2002, inventors Arakawa et al., is one where a line of stimulating electromagnetic radiation is used, and the stimulated emission is re-imaged onto a linear segmented detector such as a photodiode array or a charge-coupled device (CCD). For this line stimulation, the

pixel size is determined by the digitization rate in one direction, and by the optical imaging and detection system in the other direction.

One of the challenges for any configuration of stimulation and detection is collecting a large fraction of the stimulated emission so as to obtain high image quality. The stimulated emission is emitted in a broad angular range. For most systems, the emission is close to being Lambertian (a $\cos(\theta)$ fall off in intensity with angle of emission). For the raster-scanned systems, the typical collection systems have a large acceptance angle for the stimulated emission, and are highly reflective and shaped so that the emission is directed to a fairly large area detector, such as, a photomultiplier tube. For some systems, the collector is a light-pipe, i.e., a plastic conduit that uses total internal reflection to guide the stimulated emission to the detector. Given that the typical stimulated emission wavelength range is 350 to 450 nanometers, the plastic must have a high transmittance for ultraviolet and blue electromagnetic radiation. For the imaged line-stimulation systems, the collection optics used must have a very low f-number to collect a large fraction of the emission. This places constraints on the depth of field of such an imaging system. Also, such low f-number optics can be more expensive than higher f-number optics. If the range of emission angles could be narrowed, the collection optics could be greatly simplified, thus saving space and cost. One such method of altering the emission angle range is disclosed in U.S. Patent 6,507,032, issued January 14, 2003, inventors Hell et al., in which microlenses are formed on the surface of the screen in an attempt to narrow the range of emission angles. This technique can only slightly narrow the emission cone, and adds manufacturing cost to each screen. It also does not alter the wavelength of the emission as discussed in the next paragraph.

Another challenge is to detect the stimulated emission with very high quantum efficiency (QE). The typical wavelength of the emission is 350 to 450 nanometers. For the raster-scanned systems, the detector is typically a photomultiplier tube (PMT). The QE of a typical PMT has a value around 25% at 400 nanometers for a bi-alkali photocathode. For the re-imaged systems, typical CCD detectors have a QE at 400nm that is typically 50% or lower. If the

wavelength of the emission could be shifted towards longer wavelength, then CCD and other semiconductor detectors will detect the emission with higher QE.

SUMMARY OF THE INVENTION

According to the present invention, there is provided a solution to these problems.

According to a feature of the present invention, there is provided a storage phosphor imaging system comprising:

a source for producing stimulating radiation directed to a storage phosphor storing a latent image;

a resonant microcavity converter for converting emitted radiation from said storage phosphor to radiation at a longer wavelength than said emitted radiation but with an angular intensity distribution that is substantially narrower than a Lambertian distribution; and

a detector for detecting said longer wavelength radiation.

ADVANTAGEOUS EFFECT OF THE INVENTION

The invention has the following advantages.

1. A storage phosphor readout system is provided that results in a narrower range of stimulated emission angles and shifts the wavelength to longer wavelengths where common semiconductor photodetectors have high QE.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic diagram of a storage phosphor readout system using the flying-spot method that includes an embodiment of resonant cavity converter according to the invention.

FIG. 2 shows a cross-sectional view of the resonant cavity converter of FIG. 1.

FIG. 3A shows a side elevational view of a line-stimulation readout system incorporating a dichroic reflecting filter and a resonant cavity converter according to the invention with both stimulation and collection occurring along a direction approximately 90 degrees to the screen surface.

FIG. 3B is a diagrammatic view which shows a more distant view schematically showing more than one stimulating and detecting unit across the width of the screen of FIG. 3A.

FIG. 4 shows a side elevational view of a line-stimulation readout system using a resonant cavity converter of the invention with the stimulation occurring along a direction less than 90 degrees, and the collection occurring along a direction approximately 90 degrees to the screen without a dichroic reflecting filter.

FIG. 5 shows a cross-sectional elevational view of a configuration with the resonant converter of the invention in intimate contact with the storage phosphor screen.

DETAILED DESCRIPTION OF THE INVENTION

As described in detail herein below, the present invention provides for a storage phosphor readout system that results in a narrower range of stimulated emission angles and shifts the wavelength to longer wavelengths where common semiconductor photodetectors have high QE. The incorporation of a resonant microcavity device is used to perform this stimulated emission transformation.

Referring to FIG. 1, there is shown a storage phosphor readout system incorporating a resonant microcavity device according to the present invention. Laser **101** produces a laser beam **10** passed through an intensity modulator **102** for control of the laser exposure during the scan, e.g., turning off the laser during the retrace if a scanning galvonometer is used for laser beam steering. The laser beam **10** is then passed through beam shaping optics **103** that expand the beam to the desired size so subsequent focusing and steering optics **105** produce the desired spot size on the storage phosphor screen **107**. The laser beam is raster-scanned in a line scan across the screen **107** in the fast-scan direction by either a galvonometer scanner or a rotating polygon mirror **104**. The storage phosphor screen **107** is translated in the slow-scan direction **12** (perpendicular to the laser raster) at a rate such that the desired pixel size is obtained in the slow-scan direction. According to the invention, a resonant

microcavity converter **106** is placed in close proximity to the storage phosphor screen **107** so that the laser beam **10** passes through it. The stimulated emission from the storage phosphor screen **107** is emitted with an intensity profile that is approximately Lambertian. The phosphor emission is absorbed by converter **106** and converted to an emission at a longer wavelength than the stimulated phosphor emission, but with an angular intensity distribution that is substantially narrower than Lambertian. A Lambertian distribution is one in which the intensity of emission per unit solid angle decreases as the cosine of the angle measured from the normal to the emitting surface. Thus, a Lambertian has a full-width-at-half-maximum (FWHM) of +/- 60 degrees since the cosine of 60 degrees is 0.5. The converter **106** has an angular intensity distribution that is substantially less than Lambertian. Thus, the angular intensity distribution of the converter emission decreases faster than cosine of the emission angle. The preferred converters for this application have an angular intensity distribution with a FWHM that is less than or about +/- 45 degrees, or more preferentially a FWHM that is less than or about +/- 30 degrees.

The converter emission is collected by the collector **108** and directed towards the filter **109**. This filter blocks the laser radiation from being sensed by the detector **110**, but passes the majority of the converter emission. The detector **110** senses the converter emission and provides a signal to the subsequent digitizing electronics **111**. The entire system is controlled by the computer **112**. The image data may be viewed on the display **113**, and stored in the storage device **114**.

The converter **106** is a resonant microcavity device. Shown in FIG. 2, is a cross-section of an exemplary configuration of such a converter. As shown, converter **106** includes substrate **210** that is transmissive to both the converter emission and the storage phosphor stimulation light. The substrate **210** may be transparent glass or plastic. On the substrate **210** is deposited a bottom dielectric stack **220**, which is composed of alternating high and low refractive index dielectric materials. The bottom dielectric stack **220** is designed to be reflective to the microcavity emission over a predetermined range of wavelengths, but transmissive to the storage phosphor stimulation wavelength. Typical high

and low refractive index materials are TiO_2 and SiO_2, respectively. However, Ta_2O_5 may be used instead of TiO_2. The bottom dielectric stack **220** is deposited by standard electron-beam deposition, where a typical deposition temperature is 240°C. The organic active region **230** is deposited over the bottom dielectric stack **220**. The active region can be composed of small-molecular weight organic material, conjugated polymeric organic material, or a combination of the two. The small-molecular weight organic material is typically deposited by high vacuum (10^{-6} Torr) thermal evaporation, while the conjugated polymers are usually formed by spin casting.

FIG. 2 shows the organic active region **230** is not a bulk layer but a multilayer composite. Following the suggestions of Brueck et al. in U.S. Patent 4,881,236, issued Nov. 14, 1989, inventors Brueck et al., for inorganic VCSEL lasers, the organic active region **230** contains one or more organic periodic gain regions **260**, which are separated by spacer layers **270**. The thickness of the organic periodic gain regions **260** is typically less than 50 nm, with a preferred thickness of 5 to 25 nm. The thicknesses of the spacer layers **270** are chosen such that the organic periodic gain regions are aligned with the antinodes of the cavity's standing electromagnetic field. Employing periodic gain regions in the active region results in larger power conversion efficiencies and a large reduction in the unwanted spontaneous emission. In summary, the active region **230** includes one or more organic periodic gain regions **260** and spacer layers **270** disposed on either side of the periodic gain region(s) and arranged so that the periodic gain region(s) is aligned with the antinodes of the device's standing wave electromagnetic field. The number of active periodic gain regions is chosen to obtain the desired absorption of the phosphor's stimulated emission. The number of periodic gain regions will typically be in the range of 2 to 10.

The organic periodic gain regions **260** are composed of either small-molecular weight organic material or polymeric organic material that fluoresce with high quantum efficiency. In this embodiment it is preferred to use a host-dopant combination as the gain media since it can result (via the mechanism of Forster energy transfer) in a very small unpumped band-to-band absorption coefficient, $< 1\ cm^{-1}$ for the gain media at the emission wavelength (M.

Berggren et al., Nature 389, 466 [1997]). An example of a useful host-dopant combination for green-emitting microcavities is aluminum tris(8-hydroxyquinoline) (Alq) as the host and [10-(2-benzothiazolyl)-2,3,6,7-tetrahydro-1,1,7,7-tetramethyl-1H,5H,11H-[1]Benzopyrano[6,7,8-ij]quinolizin-11-one] (C545T) as the dopant (at a volume fraction of 0.5%). Other host-dopant combinations can be used for emission in other wavelength regions, such as in the blue and red.

For organic periodic gain regions **260** that include polymeric material, they can be composed of a single polymeric component, a blend of two or more polymeric materials, or a doped polymer or polymer blend. The gain media can also be a combination of more than one non-polymeric and polymeric materials with or without dopants. Typical dopants are listed previously for non-polymeric molecules. Non-polymeric dopants can be molecularly dispersed into the polymeric host, or the dopant could be added by copolymerizing a minor constituent into the host polymer. Typical polymeric materials include, but are not limited to, substituted and unsubstituted poly(p-phenylenevinylene) (PPV) derivatives, substituted and unsubstituted poly(p-phenylene) (PPP) derivatives, substituted and unsubstituted polyfluorene (PF) derivatives, substituted and unsubstituted poly(p-pyridine), substituted and unsubstituted poly(p-pyridalvinylene) derivatives, and substituted, unsubstituted poly(p-phenylene) ladder and step-ladder polymers, and copolymers thereof as taught by Diaz-Garcia et al. in U.S. Patent 5,881,083 and references therein. The substituents include but are not limited to alkyls, cycloalkyls, alkenyls, aryls, heteroaryls, alkoxy, aryloxys, amino, nitro, thio, halo, hydroxy, and cyano. Typical polymers are poly(p-phenylene vinylene), dialkyl-, diaryl-, diamino-, or dialkoxy-substituted PPV, mono alkyl-mono alkoxy-substituted PPV, mono aryl-substituted PPV, 9,9'-dialkyl or diaryl-substituted PF, 9,9'-mono alky-mono aryl substituted PF, 9-mono alky or aryl substituted PF, PPP, dialkyl-, diamino-, diaryl-, or dialkoxy-substituted PPP, mono alkyl-, aryl-, alkoxy-, or amino-substituted PPP. In addition, polymeric materials can be used such as poly(N-vinylcarbazole) (PVK), polythiophenes, polypyrrole, polyaniline, and copolymers such as poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) also called PEDOT/PSS.

For the spacer layer **270** it is preferred to use a material which is highly transparent to the microcavity emission **290,** the incident stimulated emission light **280** (produced by phosphor screen), and the laser light which stimulates the storage phosphor. In this embodiment an organic layer, 1,1-Bis-(4-bis(4-methyl-phenyl)-amino-phenyl)-cyclohexane (TAPC), is chosen as the spacer material, since it has very low absorption throughout the visible and near UV spectrum and its index of refraction is slightly lower than that of Alq. This refractive index difference is useful since it helps in maximizing the overlap between the standing electric-field antinodes and the periodic gain regions **260**. Other useful spacer layer materials are inorganic compounds such at SiO_2, which can be deposited thermally or electron-beam evaporation.

Following the active region **230** is deposited the top dielectric stack **240**. The top dielectric stack **240** is spaced from the bottom dielectric stack**220** and reflective to light over a predetermined range of wavelengths. Its composition is analogous to that of the bottom dielectric stack **220**. Since the top dielectric stack **240** is deposited over an organic-based active region, its deposition temperature must be kept low in order to avoid melting the organics. As a result, a typical deposition temperature for the top dielectric stack **240** is 70°C. In order to obtain good emission efficiency, it is preferred that the peak reflectivity of the top dielectric stack **240** to the microcavity emission wavelength be greater than 99%, preferably greater than 99.9% in order to prevent microcavity light emission from exiting through it. For the bottom dielectric stack **220**, in order to enhance the out-coupling efficiency, it is preferred that the stack reflectance be smaller than 99%, where further reductions in the bottom stack reflectance result in higher external efficiencies, larger spectral linewidths, and larger microcavity light emission cone angles. In summary, the bottom dielectric stack **220** should be selected so that it's peak reflectance is less than 99%. As a result, the spectral linewidth is increased, thereby resulting in improved power conversion efficiency. In fact, by lowering the bottom dielectric stack **220** peak reflectance to less than 85%, it was determined that the power conversion efficiency can be greater than 20%. For the common storage phosphor materials used with a peak stimulated

emission wavelength around 400nm, and a green emitting microcavity, this results in an external quantum conversion efficiency in excess of 30%.

As shown in FIG. 2, the microcavity converter **106** is optically driven by the stimulated emission from the phosphor screen **107** and emits light **290** with an angular intensity distribution that is substantially narrower than Lambertian. To improve the power conversion efficiency of the device, it is desirable to add additional dielectric layers to both dielectric stacks, such that the top dielectric stack **240** is highly transmissive to the phosphor emission **280** and the bottom dielectric stack **220** is highly reflective to phosphor emission. As a result of the designed converter structure, microcavity emission occurs mainly through the substrate **210**. FIG. 2 shows the microcavity emission **290** through the bottom dielectric stack **220** and the substrate **210.** Alternatively, the microcavity structure could be optically pumped through the substrate **210** and the bottom dielectric stack **220**, with the microcavity emission mainly exiting through the top dielectric stack **240** by proper design of the dielectric stack reflectivities.

With the microcavity converter **106** in close proximity to the phosphor screen as in FIG. 1, one or both of the exterior surfaces of the converter may have additional dielectric stack coatings to minimize reflection of the laser stimulating light so as to reduce flare, i.e., laser radiation hitting regions of the screen other than the desired pixel area.

The configuration shown in FIG. 1 has a generically labeled collector **108**. Collectors may be fabricated as light-pipe guides as disclosed in U.S. Patent 5,138,161, issued Aug. 11, 1992, inventors Miyagawa et al. These light-pipe guides use total internal reflection to direct the emission to the detector **110**, so the light propagates within the light-guide material. The common phosphor material used in storage phosphor screen **107** is a barium fluorohalide doped with europium. The emission of this material has a peak wavelength around 400nm, with a full width at half maximum of around 40nm, so the light-guide material of collector **108** must have a high transmission in the blue and near ultraviolet wavelength range for efficient collection, thus limiting the potential candidate materials. With the microcavity converter **106**, the emission wavelength is shifted to the green wavelengths, so more plastic materials become

candidates for fabricating the light-guide collector **108**. Also, the light-guide **108** collecting the longer wavelength microcavity converter emission may not have to be as thick as a comparable direct stimulated emission light-guide collector since the range of microcavity emission angles is much less than the approximately Lambertian shape of the stimulated emission. As a modification to the configuration shown in FIG. 1, a cylindrical lens or an array of lenses could be used to gather and redirect the microcavity emission into the light collector **108**.

In another preferred embodiment shown in FIG. 3A and 3B, a line stimulation is used and a segmented detector is used to provide the pixel definition along the line of stimulation similar to that disclosed in U.S. Patent 6,373,074, issued Apr. 16, 2002, inventors Mueller et al., and U.S. Patent application publication 2002/0008212 A1, published Jan. 24, 2002, inventors Arakawa et al. FIG. 3B shows a more distant view of the stimulation and detection system. There are multiple stimulating and detecting subsystems **300**. FIG. 3B shows the same number of stimulating light sources **301** with their associated lenses **302** and segmented detectors **305** with their associated imaging lenses **304**, but that is not a requirement of this application. There can be an unequal number of stimulating light sources and segmented detectors. As shown in FIG. 3A there is at least one stimulating light source **301**. The stimulating beam(s) are shaped into a focused line on the storage phosphor screen **107** by at least one corresponding lens(es) **302**, reflected by mirror **330** first passing through dichroic filter **303** and the microcavity converter **106**. The dichroic filter **303** transmits the long wavelength stimulating light but reflects the shorter wavelength microcavity converter emission. The microcavity converter **106** is placed in close proximity to the storage phosphor screen **107**, the spacing from the top of the storage phosphor screen **107** being in the range of 0.025 to 0.5 mm, preferably in the range of 0.025 to 0.1mm. The stimulated emission from the storage phosphor screen **107** is absorbed by the converter **106** and re-emitted by the converter **106** at a longer wavelength than the stimulated emission and in an intensity profile that is much narrower than a Lambertian. The converter emission is reflected by the dichroic filter **303** and directed towards at least one imaging lens(es) **304** that in turn focus an image of the emission onto the corresponding segmented detector(s) **305**. The

filter **309** drastically reduces the intensity of any remaining stimulating light that reaches the segmented detector **305**, but passes a significant fraction of the converter emission so it can be sensed by the segmented detector **305**. The output of the detector **305** is gathered, processed, stored, and potentially viewed by the image processing system **306**. The storage phosphor screen **107** is translated in a direction **110** perpendicular to the line of stimulation at a rate such that the subsequent readings of the system result in the desired pixel size in the scanned direction.

The segment size of the detector **305** is chosen along with the magnification provided by imaging lens(es) **304** so that the desired pixel size is obtained in the line-stimulation direction. The converter **106** in this configuration has similar properties and construction as has previously been described. To maintain the optimal gap between the microcavity converter **106** and the associated collection and detection components, and also to prevent collisions with the surface of storage phosphor screen **107**, some means of active positioning may be necessary. This active positioning function is not shown in the figure, but by its mention here is understood to be a potential component of the configuration shown in FIG. 3A.

Another preferred embodiment is shown in FIG. 4. This configuration is very similar to that shown in FIG. 3, but the dichroic filter has been removed and the stimulating light source **301** impinges on the storage phosphor screen **107** at an angle less than 90 degrees. The segmented detector **305**, the imaging lens **304** and the filter **309** are oriented so as to be at an angle greater than 90 degrees to the phosphor screen **107** and converter **106**. Considerations of the converter to screen spacing and screen transport are the same as described above for FIG. 3A.

The configurations shown in FIG. 3A and FIG. 4 have the line stimulation and collection across the entire screen width, with the screen scanned relative to the stimulation and collection system. An alternative configuration is for the line stimulation and collection system **(301, 302, 303, 106, 304, 305, 309)** to be smaller so that only a short linear segment is stimulated, with the direction of the linear stimulation line now being parallel to the screen motion direction. This

smaller stimulation and collection system is raster-scanned across the screen in a manner similar to that done for inkjet printheads in well-known inkjet printers. However, instead of laying ink down with a printer, this stimulation and detection system lays down stimulation exposure and collects and detects the corresponding emission. As mentioned above, some means of controlling the spacing between the stimulation and collection system and the phosphor screen may be needed to maintain the desired image resolution, and to prevent any collisions between the converter and the phosphor screen.

In another preferred embodiment shown in FIG. 5, the microcavity converter **106** covers, and is in intimate contact with but not optically coupled to, the storage phosphor screen **107**. The different geometrical configurations for reading out the storage phosphor screen as shown in FIG. 1, FIG. 3A and FIG. 4 can still be used, but the converter is now covering the entire screen. The advantage here is mainly for the re-imaging of the line stimulation configuration of FIG. 3A and FIG. 4. With the intimate but not optical contact between the screen and the converter, there is no loss in resolution of the re-imaged converter emission since there is no gap between the screen and the converter. For this embodiment when using the common europium-doped barium fluorohalide phosphor screens, the dielectric stacks of the converter should be designed such that some transmission in the range of 425 to 500 nanometers occurs to maximize the use of the light coming from the erase lamps since common erase lamps are broad wavelength emitters.

Although specific storage phosphor screen materials have been described that are stimulated with light at specific wavelengths and produce emitted light at specific wavelengths, it will be understood that other storage phosphor screen materials may be used having stimulating and emitting light at different wavelengths. In such case, suitable microcavity converter materials would also be used.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

10	laser beam
12	slow-scan direction
101	laser
102	modulator
103	beam shaping optics
104	rotating polygon mirror
105	steering optics
106	microcavity converter
107	storage phosphor screen
108	light collector
109	filter
110	detector
111	digitizing electronics
112	computer
113	display
114	storage device
210	substrate
220	bottom dielectric stack
230	organic active region
240	top dielectric stack
260	organic periodic gain regions
270	spacer layers
280	stimulated emission light
290	microcavity emission
300	multiple stimulating and detecting subsystems
301	stimulating light source
302	imaging lenses
303	dichroic filter
304	imaging lenses
305	segmented detectors
306	imaging processing system

309 filter

330 mirror